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Georectification of the Airborne Multi-angle Imaging SpectroRadiometer

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***Abstract*—An Airborne Multi-angle Imaging SpectroRadiometer (AirMISR) has been developed to assist in validation of the Earth Observing System (EOS) MISR instrument currently flying on the Terra spacecraft. Unlike the EOS MISR, which contains nine individual cameras pointed at discrete look angles, AirMISR utilizes a single camera in a pivoting gimbal mount. A principal requirement for AirMISR is that it must image the same area on the ground from all nine angles. The NASA ER-2 is the preferred platform for AirMISR because its flight altitude of 20 km is above more than 90% of the Earth's atmosphere. Applications of cloud screening, cloud height retrieval, and cirrus detection algorithms require a high-altitude operation. The normal variation in aircraft roll, pitch, and yaw on the ER-2 as well as changes in attitude, track direction and velocity, although small, must be measured. The measured values are used along with post-flight defined corrections in order to georectify and coregister the image data for all angles and spectral bands. This paper provides a description of the algorithm and operational aspects of AirMISR georectification along with examples and results from a recent flight.**

Keywords: Earth Science, Multi-angle, Rectification

I. INTRODUCTION

The MISR instrument was launched into polar Earth orbit aboard the Terra spacecraft on December 18, 1999. Terra is in a 16-day-repeat, 705-km, Sun-synchronous orbit and has approximately a nominal 10:30 am equator crossing time on the descending node. MISR uses nine separate charge coupled device (CCD)-based pushbroom cameras to provide multiple-angle, continuous imagery of the Earth in reflected sunlight [*Diner et al.,* 1998a]. The cameras are oriented in the following configuration: one at nadir plus eight other symmetrically placed cameras that provide fore-aft observations with view angles at the Earth's surface of 26.1°, 45.6°, 60.0°, and 70.5° relative to the local vertical. The imagery is provided in four spectral bands (blue, green, red, and near-infrared) at each angle, yielding a total of 36 image channels (9 angles × 4 bands). MISR measurements are designed to improve our understanding of the Earth's ecology, environment, and climate.

The aircraft version of MISR, called AirMISR, flies on a NASA-owned ER-2 aircraft [*Diner et al.,* 1998b]. Its primary role is to serve as a MISR simulator, providing data useful for: a) validation of MISR geophysical retrieval, b) in-flight radiometric calibration and instrument performances characterization, and c) general scientific research based on a high quality, well calibrated multi-angle imaging data. In order to reach these goals AirMISR data acquisition system must resemble multi-angle geometric attributes of the MISR. Consequently, AirMISR ground data production system must satisfy similar requirements as those defined for MISR geometric processing. More specifically, the image data associated with the nine view angles must be co-registered and geolocated (i.e. georectified) as a part of standard data production.

While there are similar needs for georectification of the images from both instruments, the operational algorithms used to process airborne data are somewhat different than the algorithms applied for the spaceborne data. The theoretical concepts, underlying the design of the MISR science data processing system, responsible for autonomous and continuous georectification have been previously described [*Jovanovic et al.,* 1998]. This paper describes specific algorithm and operational procedure adapted to georectify AirMISR data. The methods selected are designed to deal with particular conditions of the data acquisition system, such us: a) insufficiently accurate ER-2 navigation data, b) impermanent orientation between camera reference frame and INU/GPS reference frame, 3) inaccuracy of the gimbal assembly used to provide multi-angle pointing capability. The next section describes the geometry of the AirMISR imaging event. The following sections describe relevant input data, georectification aspect of data the production system, and format of the final georectified product. The following section also discusses georectification results using data from a recent flight over Steamboat, Colorado.

II. GEOEMTRY OF AIR-MISR IMAGING EVENT

The AirMISR is mounted in the nose of NASA's ER-2, which flies at 20 km altitude. The instrument consists of a single pushbroom camera mounted on a motorized pivot. In a standard operational mode a data run is divided into nine segments, each corresponding to a MISR specific angle. The camera is preprogrammed to pivot aft between segments, thus creating a viewing sequence in which data are first acquired at nominal D-forward (Df) viewing angle of 70.5° of the nadir in the along flight direction. Then consecutively stepping backwards the Cf (60°), Bf (45.6°), Af (26.1°), An (nadir), A-aft (Aa), Ba, Ca, and Da view angles, image data are acquired during a 12 min 141 km flight line. The commanded times of camera rotation and acquisition are coordinated with aircraft velocity and altitude in order to maximize overlap of the targeted ground area (*see Figure 1*).

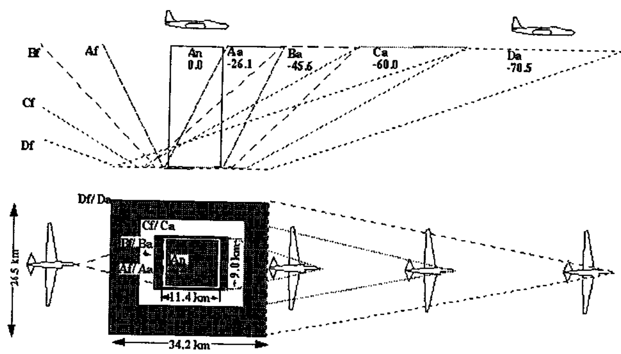


Figure 1: AirMISR image acquisition sequence represents one data run. During a single flight multiple run with different flight azimuths are acquired over one or more ground targets.

The AirMISR camera uses four charge coupled device (CCD) line arrays parallel in a single focal plane The line array contains 1504 photoactive pixels, each 21 x 18 μm. Each line array is filtered to provide one of the four spectral bands. The spectral band shapes are approximately Gausian and centered at 446, 558, 672, and 866 nm. The camera effective focal length was determined to be 58.8 mm. MTF at 20°C. For nominal ER-2 flight conditions, the AirMISR camera has an instantaneous footprint of 7 m cross track x 6 m along track when viewing in the nadir position. For the most oblique D angles coverage increases to 21 m cross track x 55 m along track. Image lines are acquired every 40.8 ms resulting in an along track sample spacing, regardless of view angle, of 8 m for a nominal aircraft ground speed of 200 m/s.

The total image swath width is defined by camera field-of-view and varies from 11 km in the nadir to 32 km at the most oblique angle. The image lengths are controlled by the timings of viewing sequence, which is set so that all nine images are centered over the same ground target. This gives a variable image length of 9 km at nadir up to 26 km at the most oblique angles.

In order to find the geolocation corresponding to pixel's field-of-view, the pixel pointing direction is expressed in the geocentric coordinate system, as follows:

$$(1)\ \hat{\rho} = T_1 \hat{r}_{acs}$$

where $\hat{r}_{acs}$ is the pixel pointing direction relative to the aircraft coordinate system (ACS) identical to the INU/GPS body axis reference frame. The vector $\hat{r}_{acs}$ is defined by the observable image coordinates and a set of constants that represent the instrument interior orientation parameters and transformation between instruments, including gimbal position, and aircraft coordinate axes. T_1, defined by the aircraft position and orientation at the time of imaging, represents the transformation between the aircraft and geocentric coordinate system. Equation (1) is the well known photogrammetric model [*Paderes et al.*, 1996] used for various image-ground point determinations required for time dependent remote sensing imagery.

III. AIR-MISR GEORECTIFICATION APPROACH

A direct geolocation of AirMISR pixels prior to rectification is not possible due to the insufficient accuracy of ER-2 INU/GPS system and instrument gimbal assembly. For the current system, a collection of ground control points is an unavoidable part of data processing operations. Our approach minimizes human involvement by requiring interactive ground control point collection only over nadir (An) image. Other images are co-rectified to the nadir via automatic tie point collection and a time-dependent trajectory model used to account for system positioning and pointing errors. This section describes input data, georectification algorithm, and output data in more details.

A. Input data

Navigation: ER-2 navigation information, supplied by Litton-92 INU/GPS system, is acquired in-flight by AirMISR as an asynchronous stream of packetized data recorded in a single file. Each packet contains a relative timestamp and a data value for a single navigation parameter. Data processing begins by reading all of the packets, decoding the timestamps and data values and extracting only the parameters needed for georectification. Aircraft attitude is updated 64 times per second. Aircraft position is updated eight times per second. Navigation data are recorded asynchronously with respect to the camera data. The ARINC 429 time stamp included in both data sets is later used to align the navigation and camera time lines during processing. The specified accuracy [*Litton Aero Products*, 1996] for the aircraft attitude and position data along with propagated geolocation error are given in *Table I.*

TABLE I
ER-2, LTN-92 INU/GPS SPECIFIED ACCURACY (2 SIGMA) AN D PROPAGATED GEOLOCATION ERRORS

PARAMETER	ACCURACY	PROPAGETED ERROR
ATTITUDE	0.05 DEG	29 M (NADIR) 170 M (D'S VIEW ANGLES)
HORIZONTAL POSITION	100 M	100 M
VERTICAL POSITION	400 M	130 M (NADIR) 1200 M (D'S VIEW ANGLE)

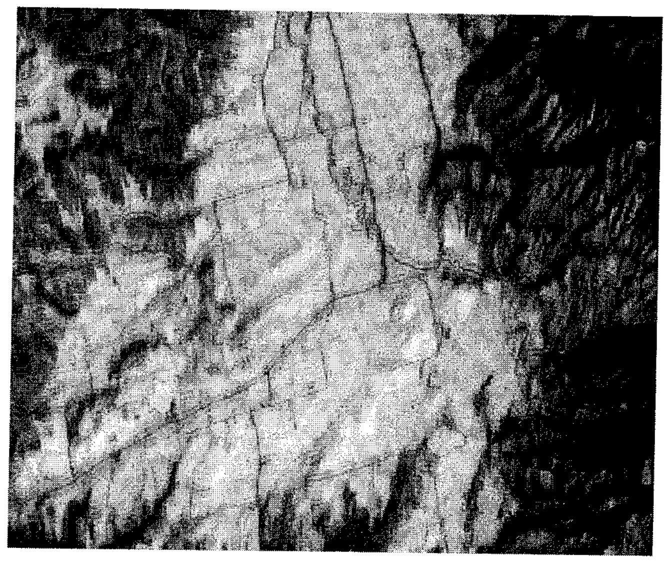
Digital Elevation Model: The AirMISR georectification relies on the already available Digital Elevation Model (DEM). Almost entire US area is covered with DEM of sufficient resolution ranging from 1 m up to 30 m elevation postings. The maximum geolocation error, resulting from the use of the existing US DEM's is less then 40 m for the most oblique view angles.

Imagery: AirMISR images input to georectification are only radiometrically corrected by radiance conversion and scaling. The red, green, and blue band image of the extreme forward-viewing 70.5° look angle is displayed in *Figure 2.*

Figure 2: Color red/green/blue image of area near Steamboat Springs, Colorado acquired on March 08, 2001 at the Df (70.5°angle.

This as acquired image shows several artifacts regarding the geometry of the imaging event. First, the data displayed do not reflect the true along-track/cross-track spatial aspect ratio since at this view the cross-track sample spacing is 21 m while along-track is 8 m. Second, there is an obvious band-to-band misregistration due to the inherent design of the camera. The third artifact is the "smeared " appearance in the along-track direction of some image segments. This kind of effect is a result of the aircraft pitch rate that compensates for the along track motion, being such that the same point on the ground is observed by multiple line times. Also, significant change of the aircraft true heading is evident at the top of the image. Comparison of AirMISR imagery with coincident ER-2 navigation shows, as expected, high correlation between artifacts and aircraft attitude and attitude rate. All of these effects are much less prominent in the imagery acquired at the angle closer to nadir. The *Figure 3* shows red/green/blue image of the same area acquired at the Ba (-26.1°) angle.

Figure 3: Color red/green/blue image of area near Steamboat Springs, Colorado acquired on March 08, 2001 at the Ba (-26.1°) angle.



This image shows only band-to-band missregistration to the viewer. All of the artifacts discussed above are corrected during georectification.

Camera Geometric Model: The Camera Geometric Model data set consists of a set of parameters that are used in a mathematical expression that gives the pointing direction of an arbitrary pixel (vector $\hat{r}_{acs}$ in *Equation (1)*). These parameters reflect geometries of the camera system and account for distortions from an ideal optical system [*Korechoff et al.,* 1996]. Namely, the elements of the camera geometric model are:

1. The rotation matrix function of the angles between camera coordinate system and aircraft coordinate system. Nominally, this is the pitch angle commanded to pivot the camera via the gimbal assembly. The angle is accurate only to 0.1° and must be corrected prior to georectification.
2. The rotation matrix function of the angles between camera and detector coordinates system.
3. The separation of a particular band from the intersection of the camera z-axis with focal plane.
4. The pixel number (i.e. boresight pixel) corresponding to the camera x-axis (y=0).
5. The detectors pitch in x direction.
6. The effective focal length.

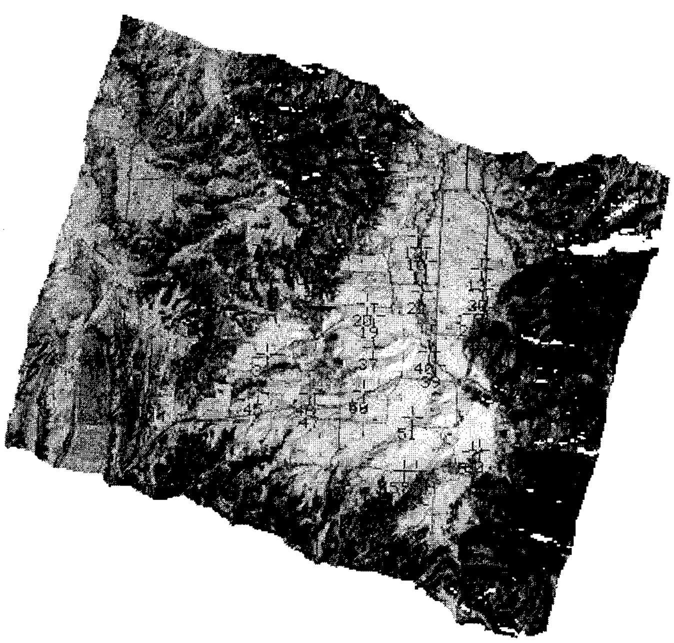
7. The coefficients of a fifth-order polynomial to account for the nonlinear distortions of the field angle in the cross-track direction.

All of these parameters, except those listed under 1, are calibrated on the ground giving the pointing accuracy corresponding to 0.2 of a pixel when projected on the ground.

Georectification Algorithm: The AirMISR georectification is divided into three parts: 1) initial georectification, 2) determination of sensor attitude and position motion parameters (i.e. exterior orientation), and 3) final georectification. In the first step, the supplied input data are used to project and resample images to the appropriate map projection. This is done on a pixel-by-pixel basis using equation (1) for the ground to image correspondence determination, and bilinear re-sampling for the assignments of the image data to the map projection grid. With this initial georectification, most of the gross image artifacts are removed and imagery as such can be used for tie point identification in order to improve camera / aircraft orientation and position.

In the case of AirMISR, with its very specific imaging sequence, the operations required to estimate exterior orientation must be designed to minimize the human involvement required for the collection of ground control points. In particular, space intersection of nadir image only, including manual collection of GCP's, is done first. Subsequently, the automatic tie points collection and simultaneous bundle adjustment for the remaining eight images are implemented as the final estimation step.

Figure 4a: Tie points collected over initially georectified image acquired at Cf (+60°) viewing angle over the target area near Steamboat Springs, Colorado.



The Landsat-4 and –5 precision geolocated terrain corrected TM scenes are used for the identification of GCP's with expected accuracy of 30 m (2 σ).

Figure 4b: Tie points collected over initially georectified image acquired at An (nadir) viewing angle over the target area near Steamboat Springs, Colorado.

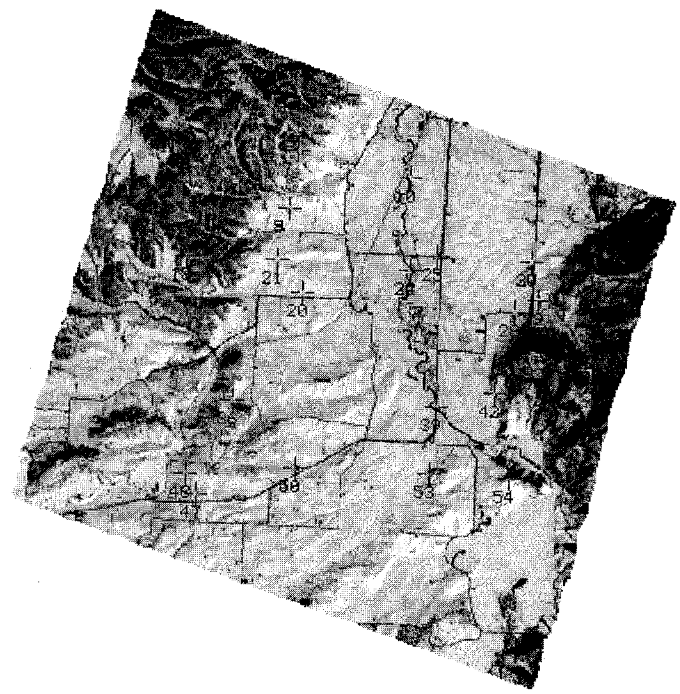
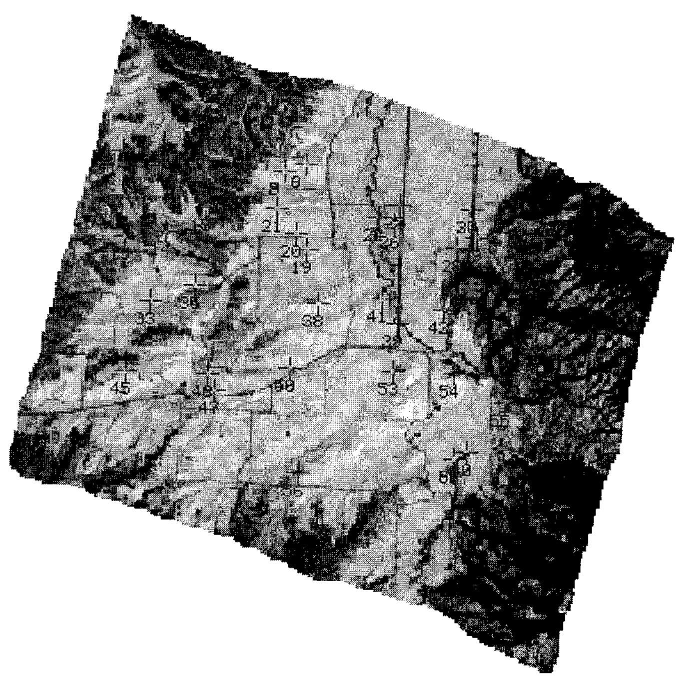


Figure 4c: Tie points collected over initially georectified image acquired at Ba (-45.6°) viewing angle over the target area near Steamboat Springs, Colorado.



The automatic tie points collection uses a combination of interest point extraction and least-square image matching to identify multi-ray conjugate points for nine AirMISR images.It should be noted that tie point collection is only possible in the initially georectified imagery due to the artifacts in the as acquired data. The figures 4 show distribution of tie points identified over images corresponding to three view angles.

The simultaneous bundle adjustment algorithm, based on Equation (1), processes tie-point measurements so that they are backward projected in *as acquired* image. This is necessary so that measurements can be related to the AirMISR camera system exterior orientation parameters via corresponding time information. The models used to correct exterior orientation parameters are chosen to be time-dependent piecewise linear functions. These functions sufficiently model error behavior in the supplied data and at the same time do not require a large number of conjugate points.

As the last step, estimated corrections to the exterior orientation parameters are used as the input to the final georectification assuring desired subpixel geolocation accuracy across all nine images. It should be pointed out that for the purpose of bundle adjustment only red band data are considered. There is no need for adjustment of the camera geometric model parameters required for band-to-band registration. Their ground calibration is sufficiently accurate and determined values do not change during flight.

Output data: As the georectification output, the 36 layers (4 bands per each of nine view angles) of digital maps are generated. All layers are referenced to the same UTM map projection grid. Common resolution of the output grid is chosen to be 27.5 m. The size of the useful image data varies from view to view as it is shown in *Figure 1*.

IV. GEORECTIFICATION RESULTS FROM A RECENT FLIGHT

On March 8, 2001 AirMISR flew over an area near Steamboat, Colorado, in support of a remote sensing research campaign requiring multi angle data over a predominately snow and ice surface. During the flight, ER-2 made four runs over the same ground target flying along different ground azimuth for each of the runs. Each run completed full image acquisition sequence generating nine images corresponding to nine view angles. The data from run 2 acquired at 205° azimuth are used to show results of AirMISR triangulation and orthorectification.

The orthorectified Landsat TM scene (p035r032) is used to collect 12 ground control points, which are then identified in nadir imagery. As the result of the space resection for nadir image, static corrections to the supplied data are as provided in *Table 2.*

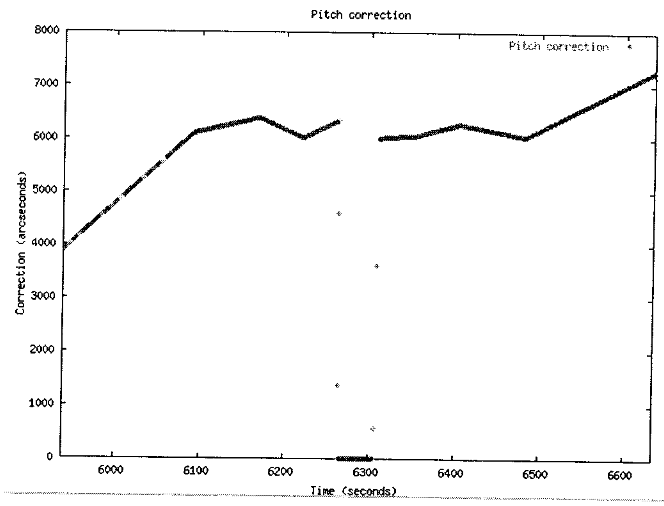
TABLE 2: STATIC CORRECTION TO THE AIR-MISR DURING IMAGING AT NADIR ANGLE

PARAMETER	ROLL	PITCH	YAW	POS (X)	POS (Y)	HEIGHT
CORRECTION	-0.553°	-1.548°	-0.076°	-101	70	263

These corrections provide improvement of georectification accuracy for nadir image from 1000 m down to within the 27.5 m size of output pixel.

The following step, simultaneous bundle adjustment, uses tie point measurements in order to estimate dynamic corrections to the exterior orientation parameters for the entire imaging sequence. During the adjustment, orientation of the nadir camera recovered in the previous step is held fixed, assuring absolute georectification accuracy of the entire image collection. As an example of our estimate in this case, the pitch corrections are given in Figure 5.

Figure 5: Estimated time dependent correction to the AirMISR pitch orientation during 12 min imaging run over the area near Steamboat Springs, Colorado.



The red line in the middle on the bottom of the graph represents the fact that orientation of the imaging system, corresponding to nadir viewing time, is held fixed during adjustment. The changes in the slope of the graph correspond to the commanded camera-viewing angle. The magnitude of the slope change can be explained with the accuracy of the pivoting mechanism.

Once estimated, the corrections to the exterior orientation are used as the input during final georectification. Figures 6a and 6b can be used to show changes in co-registration accuracy prior to and after the adjustment. Each picture represents a color composite constructed from the red band data layers associated with the three viewing angles. Df layer is color-coded red, An layer is color-coded green, and Da layer is color-coded blue. Only the bottom third of the picture represents the area where layers from all three views overlap. The figure 6a is a composite of image layers prior to adjustment, while figure 6b is a composite of the image layers after adjustment.

The misregistration of the various surface features is obvious when looking at the image in Figure 6a. In comparison, all of the line and other features in figure 6b align within the pixel size of 27.5m.

Figure 6a: Red/Green/Blue color composite of Df, An, and Da image layers prior to adjustment.

Figure 6b: Red/Green/Blue color composite of Df, An, and Da image layers after adjustment.

V. SUMMARY

The primary objective of the AirMISR instrument is to acquire image data, which, to the extent possible, match the data acquired by the senior spaceborne instrument. This objective and available budget were two driving forces behind the design of the instrument and the selection of its host airborne platform. The georectifiction objectives are perceived reachable via data production system in spite of not fully adequate pivoting mechanism and the INU/GPS navigation system inherited with NASA ER-2 aircraft. In addition to that, the AirMISR unique image acquisition sequence represents the georectification challenge in its own right. In the approach presented here, the collection of ground control points is reduced to the nadir-viewing image only. It is also shown that successful automatic collection of the remaining eight images tie points is possible only if these images are initially georectified using the supplied navigation. Finally, selection of the time dependent linear piecewise functions for exterior orientation modeling provides results, which meet georectification accuracy requirements for AirMISR imagery.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the efforts of the MISR / AirMISR Principal Investigator, D. Diner, Instrument Scientist C.Bruegge and the members of the Science Data System Team: M. Bull, S. Adams, and E. Hansen. This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. For further information, see the MISR web site at http://www-misr.jpl.nasa.gov.

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